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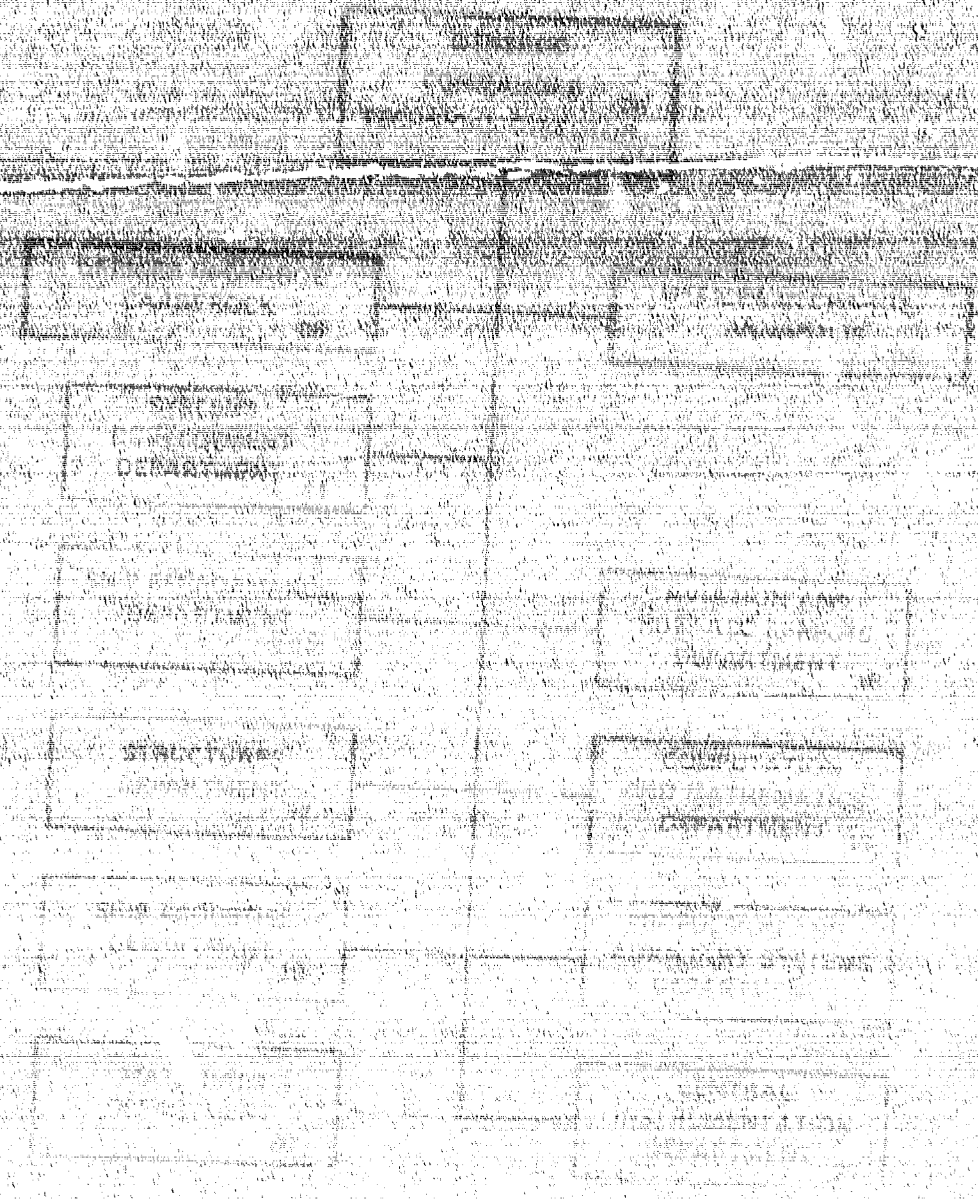

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Cam Type Valving System, Dual Receiver
Pressure Modulation
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Evaluation Criteria for Two Stepped Cam Valving System
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(Block 20 continued)

discussed and a tradeoff is presented between two control systems which have potential for the necessary requirements. A cam-collector nozzle system is considered a better choice for the model rotor configuration than a cam-collector ring control system. It was concluded that a system to control the RB-CCR wind tunnel model can be designed by employing the proper area relationships and adhering to a simple design procedure.

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NOTATION

A_{anl}	Internal annulus area, in square inches
A_c	Control area, in square inches
A_e	Exit area, in square inches
A_{gap}	Area due to gaps between the cam and upper edge of the nozzles, in square inches
A_{out}	Total nozzle flow area, in square inches
A_{web}	Area of the webs which support the upper cam contoured surface, in square inches
a_n	Fourier coefficients
b_n	Fourier coefficients
H	Nozzle height, in inches
K	Higher harmonic content factor
N	The number of blade nozzles; generally equal to the number of blades
P	Nozzle periphery, in inches
P_b	Blade pressure, in pounds per square inch
P_h	Hub pressure, in pounds per square inch
R_{cam}	Cam radius, in inches
r	Nozzle radius, in inches
r_ℓ	The average radius of the lower cam step
r_u	The average radius of the inside of the upper cam step
W	Nozzle width, in inches
α	Included angle between nozzle sides, in degrees
Δr	Gap between the cam and the nozzle
Ψ	Azimuth position, in degrees

Subscripts

1	Leading edge
2	Trailing edge
u	Upper cam
ℓ	Lower cam
cam	Cam
col	Collective

ABSTRACT

A pneumatic valving system has been developed to provide cyclic and collective control inputs for a circulation control type rotor over an advance ratio range of 0 to 2.0. The design method and experimental techniques utilized in developing the control system for a wind tunnel model of the reverse-blowing circulation control rotor (RB-CCR) are discussed and a trade off is presented between two control systems which have potential for the necessary requirements. A cam-collector nozzle system is considered a better choice for the model rotor configuration than a cam-collector ring control system. It was concluded that a system to control the RB-CCR wind tunnel model can be designed by employing the proper area relationships and adhering to a simple design procedure.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The development of a circulation control (CC) airfoil for use in a helicopter rotor system without conventional swashplates and associated pitch linkages has generated the requirement for a pneumatic valving system to provide the standard cyclic and collective inputs. The first-generation, moderate-speed rotor designated circulation control rotor (CCR) employs a single trailing edge slot. The azimuthal variation in flow through the blades is completely controlled by the varying area generated by the nozzles moving in proximity to the cams.[1,2] This technology is being extended to higher forward flight speeds in which advance ratios greater than one are encountered. At speed approaching 400 knots, the retreating side of the rotor is in reverse flow (flow

[1]Reader, K.R., "Evaluation of a Pneumatic Valving System for Application to a Circulation Control Rotor," NSRDC Report 4070 (May 1973).

[2]Wilkerson, J.B. et al., "The Application of Circulation Control Aerodynamics to a Helicopter Rotor Model," Paper 704, 29th Annual Forum of American Helicopter Society, Washington, D.C. (10-11 May 1973).

coming toward the trailing edge) and an additional slot is required on the nose section of each rotor blade. This unique feature of the reverse-blowing circulation control rotor (RB-CCR) which employs two slots and two separate control capabilities differs dramatically from the CCR. The valving system of the RB-CCR azimuthally programs the airflow to the leading edge slot, to the trailing edge slot, or to both slots of a dual-slotted rotor blade. The system still retains a cam-nozzle relationship to provide the harmonic content necessary in the airflow to control the rotor.

BACKGROUND

The initial design of the RB-CCR valving system called for a system that could provide nearly every possible control combination, but airflow programming to the leading and trailing edge slots was very ill defined. Various valving concepts were considered for possible application, e.g., (1) sleeve valves, (2) cam driver poppet valves, (3) on-off (bang-bang) type valves, (4) cam nozzle valves, and (5) fluidic valves. Selection of the valving systems was also constrained by acceptable controllability and packaging within the existing CCR model hub. Design procedures, valving data, and existing hardware were available from previous CCR tests for use in selecting various initial design configurations.

PRELIMINARY DESIGN ANALYSIS

GENERAL REQUIREMENTS

A general controllability requirement was that each leading and trailing edge duct must have a constant airflow, a 1P airflow, and a 2P airflow. If each duct was controlled separately, then the blowing of the leading and trailing edge ducts would be completely independent. Coupled with azimuthal blowing for each duct, this would constitute an ideal system. When these requirements were imposed on the conceptual valving systems, the most promising system was a two-cam system to control airflow through a collector ring common to both ducts; see Figure 1. Both the cams and collector ring would be in the stationary reference frame. The modulated airflow would be sampled in the rotating reference frame of the rotor system by nozzles which directed it to the leading and trailing edge ducts.

The airflow modulation principle would be the same as that used in the previous CG rotor models. Initially, the programming of leading and/or trailing duct blowing at specific azimuth positions was to be accomplished by a sleeve-type ring located between the rotating and non-rotating interface of the rotor. This system would have a 1P cam and a 2P cam which would control their respective components of airflow. The collective blowing would be controlled by the area of the collector ring which was not covered by the two cams. Since ample house air is available, pressure recovery between the hub plenum and the blade ducts was not a primary concern, but it was felt that the system should have a minimum pressure recovery of at least 0.70.

STRATIFICATION

A partial valving model of this system was constructed to evaluate the spacing of the collector ring sections and to determine the pressure recovery factor. Although the valving model was relatively crude, the results were adequate for evaluating the validity of the selected system. Results for various combinations of hub pressure, cam azimuth angle, and collective blowing showed that the pressure recovery was adequate, but they also revealed that airflow rates to the leading edge and trailing edge ducts were unequal for the same hub pressure. Known as airflow stratification, this phenomonon is caused by the incomplete mixing of the collective and cyclic components of the airflow delivered through the cam-collector interface (see Figure 1).

Experiments were subsequently conducted to determine an adequate means of reducing and/or eliminating stratification. The initial results indicated that the collector ring was effective in reducing stratification in the rotor azimuth range for maximum blowing (180 to 360 degrees).

The addition of various sizes of vortex-generating screens to the collector ring did not further reduce the stratification of the airflow between the leading and trailing edge ducts.*

CAM-COLLECTOR RING CONTROL SYSTEM

These encouraging results led to construction of a more refined cam-controlled valve model which enabled an evaluation of (1) the effect of reduced cam size (approximately one-half the diameter of those used in previous rotor models), (2) the techniques for incorporating this control system into the existing rotor testing system, and (3) the dynamic effects of the collector ring on the airflow from the hub to the blade ducts. This breadboard valving system was the same scale and size as the system that would be used in the existing rotor head. Photographs of the breadboard valve are shown in Figure 2. The configurations tested included three cams, single and dual ducts, and three downstream loading conditions. The parameters that were varied included rpm, hub pressure, and percent control input. The model hub valving system provided significant data for the evaluation of (1) stratification, (2) maximum pressure recovery in the blades, (3) pressure wave shape, and--most important--(4) on-off blowing for each blade duct. The last aspect resulted in a two-point design which required either a modification to the existing collector ring or a new design approach.

ROTOR CONTROL REQUIREMENTS

Development of the theoretical rotor analysis provided more specific guidelines for appropriate azimuthal airflow programming over the entire flight regime. Even though they involved some overlap, three areas were defined: low advance ratio ($0 < \mu < 0.5$), transitional advance ratio ($0.5 \leq \mu \leq 1.2$), and high advance ratio ($\mu > 1.2$). In the low advance ratio range, only the trailing edge duct would be blown and the pressure wave would be basically a 1P sine wave. In the transitional range, the

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*The author expresses appreciation to Mr. Stephen Hupp for his assistance in the execution of the initial stratification tests.

trailing edge duct would be blown from 0 to 360 degrees azimuth and the leading edge duct from approximately 180 to 360 degrees (0 degree being at the rear of the rotor disk). In the dual-blowing range, the pressure waves in both ducts would be the same; the inclusion of a 2P pressure component has been shown to be beneficial for this portion of the flight regime. In the high advance ratio range, the trailing edge duct would be blown from 0 to 180 degrees and the leading edge duct from 180 to 360 degrees; the pressure wave would be basically a 1P sine wave in both ducts, with minimum blowing occurring within 0 to 180 degrees and maximum blowing within 180 to 360 degrees (see Figure 3).

The RB-CCR forward flight data indicated that proper phasing of the 1P and 2P pressure signals can produce a single, hybrid cam design with only a slight degradation in overall rotor performance. This penalty involved approximately an 8-percent reduction in the total equivalent lift-to-drag ratio for a ±30-degree phasing between the 1P and 2P pressure components. This small reduction in performance seemed preferable to the mechanical complexity required to install two separate cams for this wind tunnel model. As a further check on the phasing between the 1P and the 2P pressure components, data from the CCR wind tunnel test were reviewed to determine the position of maximum blowing for various thrust coefficients, advance ratios, and shaft angles (see Figure 4). With an increase in thrust, maximum blowing moved toward the 270-degree rotor position for all advance ratios. The CCR model data showed that at an advance ratio of 0.5, the range of azimuth for maximum blowing was between 282 and 294 degrees. Indications were that as μ increased beyond 0.5, this position would move toward 270 degrees. Therefore a 90-degree phasing between the 1P and 2P components should ensure that the 2P input remains at an approximate azimuthal angle of 180 degrees. Based on these important results, it was decided to fabricate the 1P and 2P modulation components onto one cam.

The RB-CCR forward flight prediction program was also used to establish the magnitude of 2P control input which tended to reduce compressor power. The minimum compressor power occurred when the 2P pressure component was equal to approximately 50 percent of the 1P pressure component. The pressure wave had two maxima 120 degrees apart. This 2P cam configuration was fabricated for the RB-CCR model. Another 2P cam configuration was fabricated to maintain a maximum pressure for the entire 120 degrees of azimuth. A comparison between the desired pressure waves, as indicated by the rotor performance program and the RB-CCR cam design program, showed very good agreement (Figure 5).

CONTROL SYSTEM SEALS

Following verification of the RB-CCR control system, an analysis of the seals for the hub-valve was initiated. The breadboard control system had not addressed three design areas: (1) the best type of seal to be used between the leading and trailing edge ducts at the nonrotating interface, (2) the installation and sealing of the sleeve-type programming rings, and (3) sealing of the section dividers of the collector ring at the rotating interface.

Initial indications were that the seal between the ducts and the nonrotating interface would not present difficulties.

The sleeve-type programming rings were to be thin cylinders manufactured from steel into which windowlike holes would be cut. These sleeves would be used to azimuthally program the airflow to the leading and trailing edge ducts and would be located in the nonrotating reference frame. The programming rings would regulate only the on and off positions for the airflow and not control its amount, shape, or phase. These rings would be difficult and expensive to manufacture.

Technology for the divider section seal was found to be complicated by the sleeve programming ring in that sealing was required for a varying gap range from a minimum of 0.005 inch to a maximum of 0.100 inch. No commercial type of seal is available that would function satisfactorily on the section dividers. Because of the seal limitations caused by the sleeve-type programming rings, it was agreed that this method would be used only as a last resource.

FINAL DESIGN ANALYSIS

EVALUATION CRITERIA

Development of the final form of the control system was based on the initial experimental results from the breadboard models and the required pressure distributions from the analytical rotor prediction program. This finalized concept was evaluated against five major criteria:

1. Minimal stratification of pressure between the leading and trailing edge ducts.
2. Varying area ratio A_c/A_e with azimuth position during opening and closing of the ducts.*
3. Maintainance of proper pressure wave shape throughout all flight regimes.
4. Maximum pressure ratio $(P_b/P_h) \geq 0.75$.
5. Minimal effort for seal technology.

The initial cam collector concept which had already been experimentally tested was reexamined with these criteria in mind.

CAM-COLLECTOR RING CONTROL SYSTEM

This initial concept showed promise except for the varying area ratio and potential seal difficulties. Figures 6 and 7 indicate the effects of cycling the ducts on and off. Assuming that both slot exit areas are equal, the maximum design point for the dual-duct configuration is as shown in Figure 6. This area incompatibility can be reduced by designing the control system for dual-duct blowing to operate over the same range as the single-duct blowing. However, this leads to a pressure wave which has a significant amount of higher harmonic content. The RB-CCR requires a relatively large percentage of 2P blowing, and it would be very difficult to design a cam-collector ring system capable of maintaining the amount of blowing required. The pressure transition of single- and dual-duct blowing is shown in Figure 7. This type of pressure control is unacceptable. In addition, some mixing devices would

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*The varying area ratio resulted from the transitional advance ratios between 0.5 and 1.2 where the leading edge duct required blowing only between 180 and 360 degrees azimuth while the trailing edge duct required blowing for 360 degrees.

be needed in the collector ring to minimize stratification and some means other than the programming rings would be required to azimuthally program leading and trailing edge duct blowing.

It was concluded from the control input data of the breadboard that the cam-collector ring valve would give marginal success when incorporated into the model rotor. This system was therefore modified to provide a better method for accepting the varying area ratio requirements.

CAM-COLLECTOR NOZZLE CONTROL SYSTEM

After quantifying the shortcomings of the earlier design, a new valving arrangement was developed which employed a stepped cam and isolated air passages from the cam to each blade duct as shown in Figure 8. A significant benefit from this approach is that the maximum and minimum area ratios remain the same for any given design. The cam-collector nozzle imposes more restrictive relationships between the cam eccentricities and the height and width of the controlling nozzle. Since the RB-CCR was still in the early stages of development, it was convenient to assume that the <u>same</u> pressure wave shape would suffice for both the leading and trailing edge ducts. If more sophisticated programming is desired, this new concept will allow for different pressure wave forms in each duct. (This latter possibility was impossible with the cam-collector ring valve system.)

The cam-collector nozzle control was selected for incorporation in the model rotor. However, equations relating five design parameters were required to ensure the proper and linear control signal to both ducts from a single controller. There relationships were used to trade off various lengths, heights, and angles while maintaining compatibility with the existing model rotor head. The first requirement is that when the cam is completely removed from in front of the nozzles, the total open nozzle area of the two ducts must be equal. This will ensure that both ducts will receive equal amounts of airflow. This requirement is mandatory only when the nozzle area is equal to or greater than the control area. The second requirement is that the control area versus the percent control input for each nozzle must plot as a smooth continuous curve, preferably linear, for all cam axial positions. This requirement needs to be satisfied at all times. The third requirement is then when controlled by one cam, the collective and cyclic control areas for both ducts must be simultaneously compatible. This requirement is necessary to ensure a linear and equal airflow into each of the ducts. These requirements eliminate stratification of airflow between the leading and trailing edge ducts. Constraining the control system to fit in the existing rotor head led to a fourth requirement, namely, that airflow to the upper cam must be supplied through internal cam ducting. Each of these requirements is now discussed separately, and an illustrative example is given in the Appendix.

Collective Control Area

The geometric areas of the leading and trailing edge nozzles should be equal when the nozzles are completely uncovered, i.e.,

$$H_1 W_1 = H_2 W_2 \tag{1}$$

Equation (1) ensures area compatibility between the nozzles of the leading and trailing edge ducts.

Modulated Control Area

When the cam completely covers the nozzles, the control area for each individual nozzle is composed of the total peripheral length P of the nozzle times the gap Δr between the cam and the nozzle. The periphery of the nozzle is

$$P = 2 (H + W) \tag{2}$$

where $W = r\alpha$ is the nozzle width defined by its radius and included angle α.

$$P = 2\ (H + r\alpha) \tag{3}$$

Figure 9 shows the sensitivity of the parameters which define the peripheral length and indicates that a range of included angles, radii, and heights is established for a given packaging size. The control area for a nozzle completely covered by the cam is defined by

$$A_c = P\ \Delta r$$

or

$$A_c = 2\ (H + W)\ \Delta r \tag{4}$$

If the two nozzles are to have the same control area A_c for the same gap Δr, then the height and width must be related by

$$H_1 + W_1 = H_2 + W_2 \tag{5}$$

If the nozzles have different gap Δr's, then

$$H_1 + W_1 = (H_2 + W_2)\ \frac{\Delta r_2}{\Delta r_1} \tag{6}$$

Equations (4) through (6) can be used to relate the height, width, and gap for the two nozzles <u>as long as both nozzles are completely covered</u> by the cam. These equations will ensure that the geometric areas between the two cam-covered nozzles are equal, but there is no guarantee that the area for even a single nozzle will remain compatible where the cam is removed from the nozzles to introduce collective blowing.

Combined Control Area

For the cam-collector nozzle valve, collective blowing is introduced by raising the cam to uncover a portion of the nozzle. As the cam is raised, the tradeoff between the collective and cyclic control areas is a function of nozzle height, nozzle width, and the gap between the cam and nozzles. To determine this relationship, a common solution is needed between the areas controlled and not controlled by the cam. Assuming for a moment (and only for purposes of analysis) a single nozzle and cam, then the desired relationship between the uncovered and covered control areas is

$$A_{c_{(\text{no cam})}} = A_{c_{(\text{cam})}} \tag{7}$$

or, from Equations (1) and (4),

$$H\,W = 2\,(H + W)\,\Delta r$$

Solving for the gap Δr, we find

$$\Delta r = \frac{H\,W}{2\,(H + W)} \tag{8}$$

If the nozzle has some arbitrary collective blowing, then

$$A_{c_{(\text{no cam})}} = A_{c_{(\text{cam})}} + A_{c_{(\text{col})}}$$

and

$$H = H_{cam} + H_{col}$$

Thus

$$H\,W = \Delta r\,(2H_{cam} + W) + H_{col}\,W$$

Solving for Δr yields

$$\Delta r = \frac{H_{cam}\,W}{2H_{cam} + W} \tag{9}$$

Equations (8) and (9) relate the nozzle geometry to the gap such that there will be area compatibility for a given nozzle and cam configuration.

To ensure area compatibility between the leading and trailing edge nozzles with and without the cam, the comparable area equations for the two cases are solved simultaneously as follows:

$$A_{c1} = A_{c2}$$

$$H_1 W_1 = H_2 W_2 \text{ without cam} \tag{10}$$

$$W_1 = \frac{H_2}{H_1} W_2 \tag{11}$$

$$\Delta r_1 (H_1 + W_1) = \Delta r_2 (H_2 + W_2) \text{ with cam} \tag{12}$$

Substituting Equation (11) into (12) and solving for H_1 yields

$$H_1 = \frac{1}{2} \frac{\Delta r_2}{\Delta r_1} (H_2 + W_2) \pm \frac{1}{2} \left[\left(- \frac{\Delta r_2}{\Delta r_1} (H_2 + W_2) \right)^2 - 4 H_2 W_2 \right]^{1/2} \tag{13}$$

The roots of interest in Equation (13) are for real values. For the radical of Equation (13) to be positive:

$$\frac{\Delta r_2}{\Delta r_1} = \frac{2\sqrt{H_2 W_2}}{(H_2 + W_2)}$$

and, using Equation (12),

$$H_1 = \frac{\Delta r_2}{\Delta r_1} (H_2 + W_2) - W_1$$

$$H_1 = 2\sqrt{H_2 W_2} - W_1$$

For $W_1 \leq H_1$,

$$H_1 \geq \sqrt{H_2 W_2} \tag{14}$$

or

$$W_1 \leq \sqrt{H_2 W_2} \tag{15}$$

By selecting H_2, W_2, and Δr_1 and using Equations (9) through (15), a general design can be obtained that ensures control area compatibility.

It is instructive to examine the simpler case of equal gap for the two nozzles (i.e., $\Delta r_1 = \Delta r_2$). Equation (13) then becomes

$$H_1 = 1/2\ (H_2 + W_2) \pm 1/2\ [(-\ (H_2 + W_2))^2 - 4\ H_2\ W_2]^{1/2} \tag{16}$$

and the solution is

$$H_1 = H_2 \text{ or } H_1 = W_2 \tag{17}$$

At first glance it seems a simple matter to keep the areas between the two ducts equal when $\Delta r_1 = \Delta r_2$, namely, either $H_1 = H_2$ and $W_1 = W_2$ or $H_1 = W_2$ and $H_2 = W_1$. Remembering that $W = r\alpha$, however, we find that there are many geometric combinations of r_1, α_1, r_2, and α_2 that will satisfy Equation (12). A major physical reason why r_1 cannot equal r_2 is that the same amount of collective blowing has to be emitted into both the leading and trailing edge ducts from a common up-and-down motion of the cam. In order for Δr_1 to equal Δr_2, either the collective blowing would need to be controlled separately from the cam or the cam would need to be split into two pieces so that collective blowing could be emitted through its center. The latter configuration of the cam would be very complex to develop and build, but it would eliminate the problem of stratification.

In general the equations developed above are very useful in the preliminary design of a dual-duct valving system, but there is an ever-present and continuing compromise of the design by packaging size, mechanical complexity, material availability, and suitable fabrication techniques. To ensure the best possible design of the RB-CCR valving system, a merging of the physical system is needed within the guidelines of the equations governing area compatibility between the two ducts and between the variation of collective and cyclic areas.

Internal Cam Areas

The cam-collector nozzle valve requires that the upper interior part of the cam be hollow in order to supply airflow to the upper duct and the top of the lower duct (see Figure 8). This is most important when collective blowing is introduced to ensure adequate airflow without starvation. Air in the interior of the cam can become choked as it passes through an annulus formed by the internal surface of the upper step and the external surface of the lower step. By equating the area of this annulus to the total area being fed by the annulus, a relation can be established which will eliminate choked conditions. The area of the annulus is

$$A_{anl} = \pi(r_u^2 - r_\ell^2) + A_{gap} - A_{webs}$$

and the area being fed by the annulus is

$$A_{out} = N\ (H_u\ W_u) + A_{gap}$$

The gaps between the cam and upper edge of the nozzles (which constitute the area = A_{gap}) are approximately equal and tend to cancel each other; therefore they will be neglected. The area lost due to the webs can be neglected because the webs are undercut sufficiently to allow full airflow through the annulus.

Equating the annulus area to the total nozzles flow area yields

$$A_{anl} = A_{out}$$

$$r_u^2 - r_\ell^2 = \frac{N}{\pi}\ (H_u\ W_u)$$

For moderate airflows, the area ratio A_{anl}/A_{out} should be two or greater to ensure that both ducts receive the same collective and modulated airflow, i.e., no stratification of the airflow.

Cam Contour Definition

The contouring of the cam face was defined* in a similar manner to previous rotor systems. However, because of the dual blowing and the need for a collector nozzle, the cam diameter was only one-half as large as previous models; thus a larger azimuth angle was required in order for the effective nozzle to maintain about the same control area. From a practical standpoint, an included nozzle angle of 45 degrees was selected. The determination of control area must then consider the variation in gap (Δr) across 45 degrees rather than assume a single constant gap dimension for each control position. The cyclic control area is then expressed as

$$A_c(\Psi) = H[\Delta r\ (\Psi - 22.5°) + \Delta r(\Psi + 22.5°)]$$

$$+ 2W[\Delta r\ (\Psi - 22.5°) + 2\ \Delta r(\Psi) + \Delta r(\Psi + 22.5°)]/4$$

where $W = \frac{45°}{57.3}\ r$.

The first term shown above accounts for the two sides of the effective nozzle, and the second term accounts for an average area across the top and bottom of the nozzle. The $A_c(\Psi)$ distribution is determined from the rotor performance program, namely, roll and pitch trim requirements. The $\Delta r(\Psi)$ distribution is to be determined. These are related as follows:

$$A_c(\psi) = A_o + A_1\ \sin\psi + B_1\ \cos\psi + A_2\ \sin 2\psi + \ldots$$

$$\Delta r(\Psi) = a_o + a_1\ \sin\ \Psi + b_1\ \cos\ \Psi + a_2\ \sin\ 2\ \Psi + \ldots$$

*The author expresses appreciation to Mr. Joseph B. Wilkerson who collaborated on the material presented in this section.

Then the $\Delta r(\Psi)$ coefficients are related to the $A_c(\Psi)$ coefficients as

$$a_i = A_i/D_i \qquad i = o,N$$

$$b_i = B_i/D_i \qquad i = 1,N$$

where $D_i = (2\ H + W) \cos\ (i \times 22.5°) + W$.

This relation shows that the cam shape contains only the harmonic terms of the A_c distribution and that the azimuth angle width of the nozzle (45 degrees) will allow reasonable cam shapes up to $i = 3$ (third harmonic). Beyond $i = 3$, the D_i term becomes a very small value which drives the $\Delta r(\Psi)$ coefficients to extreme values. This does not pose any difficulties for the harmonic range of interest for RB-CCR. Once $\Delta r(\Psi)$ is obtained, the cam shape is simply defined by:

$$R_{CAM}\ (\Psi) = r - \Delta r(\Psi)$$

CONCLUSION

It is possible to design a control system for the dual-slotted RB-CCR model by using a combination of empirical and analytical results. A cam-collector ring control system was found unsuitable for the on-off blowing requirements of the leading edge slot. Stratification of air between the leading edge and trailing edge inlet nozzles can be overcome by using a cam-collector nozzle. This system was able to provide the desired wave shape and maximum pressure ratio requirements throughout all rotor flight regimes. The necessary area relationships for the cam-collector nozzle concept are presented together with an illustrative example.

APPENDIX

CAM DESIGN EXAMPLE

The example given is for the RB-CCR configuration and associated pressure distribution for pitch and roll trim requirements.

Step 1. Determine the blade pressure distribution that is needed or desired.

a. Define a pressure distribution in the general form:

$$\frac{P_b}{P_h} = a_o + a_1 \sin \Psi + b_1 \cos \Psi + a_2 \sin 2\Psi + b_2 \cos 2\Psi + \ldots$$

$$a_n \sin n\Psi + b_n \cos n\Psi$$

For the RB-CCR model, this was truncated to

$$\frac{P_b}{P_h} = a_o - a_1 \sin \Psi + b_2 \cos 2\Psi \tag{A.1}$$

where $b_2 = K\, a_1$, K being any arbitrary percentage.

b. Solve for the azimuthal position for P_b/P_h equal to a maximum

$$\frac{d(P_b/P_h)}{d\Psi} = -\, a_1 \cos \Psi - 2\, Kb_2 \sin 2\Psi = 0$$

$$\Psi = \sin^{-1} \frac{-1}{4K} \tag{A.2}$$

For K = 0.5, Ψ = 210 or 330 degrees.

c. Select maximum and minimum amplitude for P_b/P_h

$$(P_b/P_h)_{max} = 0.85, \quad (P_b/P_h)_{min} = 0$$

d. Solve Equation (A.1) for both $(P_b/P_h)_{max}$ and $(P_b/P_h)_{min}$

$$0.85 = a_o - a_1 \sin (210°) + 0.5\ a_1 \cos 2\ (210°)$$

$$0.85 = a_o + 0.75\ a_1$$

$(P_b/P_h)_{min}$

$$0 = a_o - 1.5\ a_1$$

Therefore,

$a = 0.56667$

$a = 0.3778$

and

$$P_b/P_h = 0.5667 - 0.3778 \sin \Psi + 0.18889 \cos 2\Psi \qquad \text{(A.3)}$$

Step 2. Calculate the control area A_c as a function of azimuth position.

a. Evaluate Equation (A.3) for every 30-degree increment

b. Use Figure 10 to determine the corresponding A_c/A_e

c. For duct slot area A_e, determine A_c

$$A_c = (A_c/A_e)\ A_e$$

Ψ	P_b/P_h	A_c/A_e	A_c
0			
30			
↓			
330			

Step 3. Read the control areas determined in Step 2 into the RB-CCR hub valve design program. This program performs a Fourier analysis on the area, transforms the area coefficient into Δr coefficients which are a function of the collector nozzle geometry, and uses these Δr's to calculate the designed control area.

Step 4. Using the calculated control area, calculate the area coefficients A_c/A_e by using the slot area of the blade.

Step 5. From Figure 10, look up the pressure coefficient using the area coefficients calculated in Step 4.

Step 6. Check these pressure coefficients against those desired.

Step 7. The contour of the cam is given by

$$R_{cam} (\Psi) = r - \Delta r (\Psi)$$

Note the good agreement between the desired pressure waves and the pressure waves from the design as presented in Figure 5.

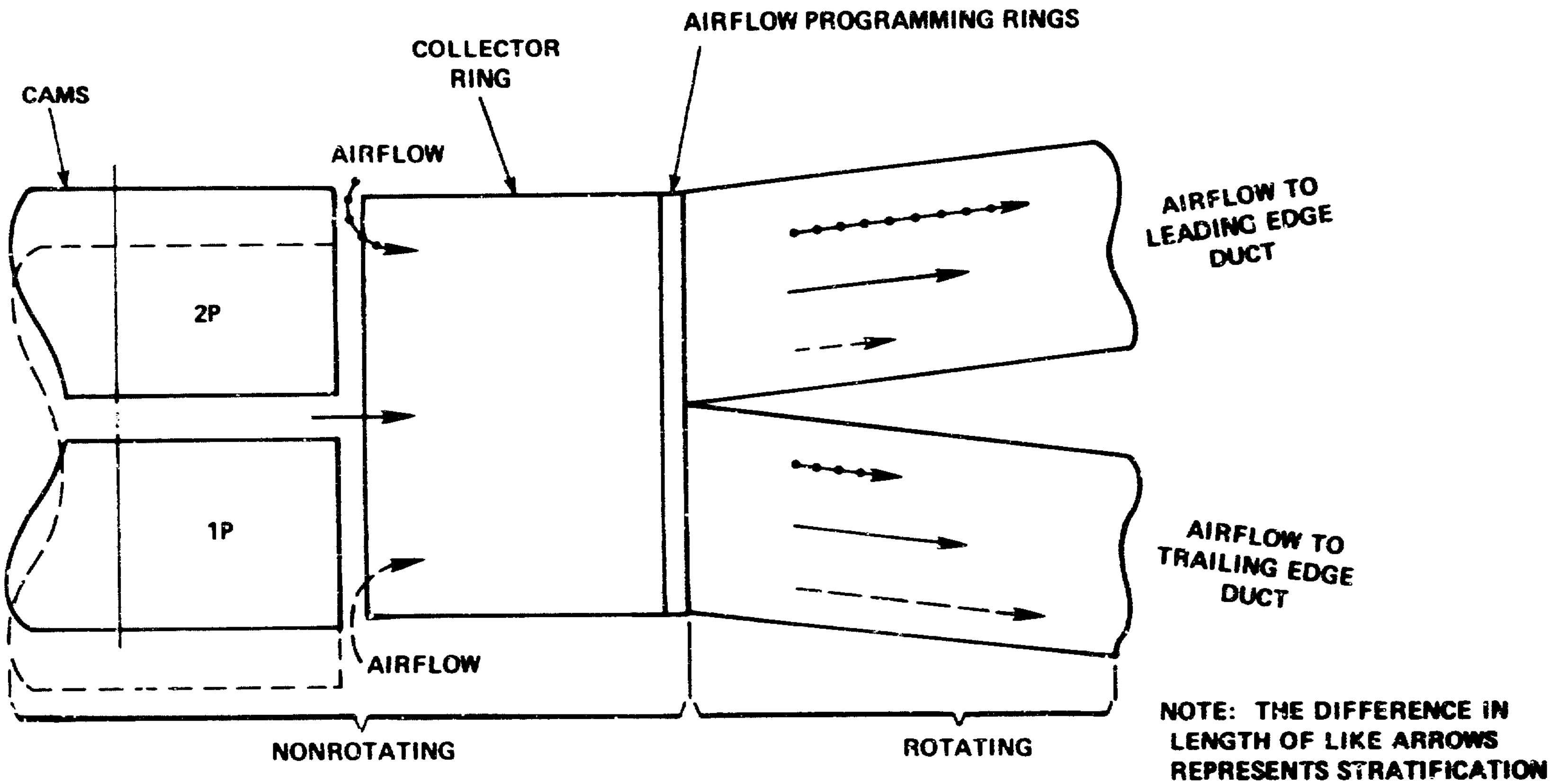
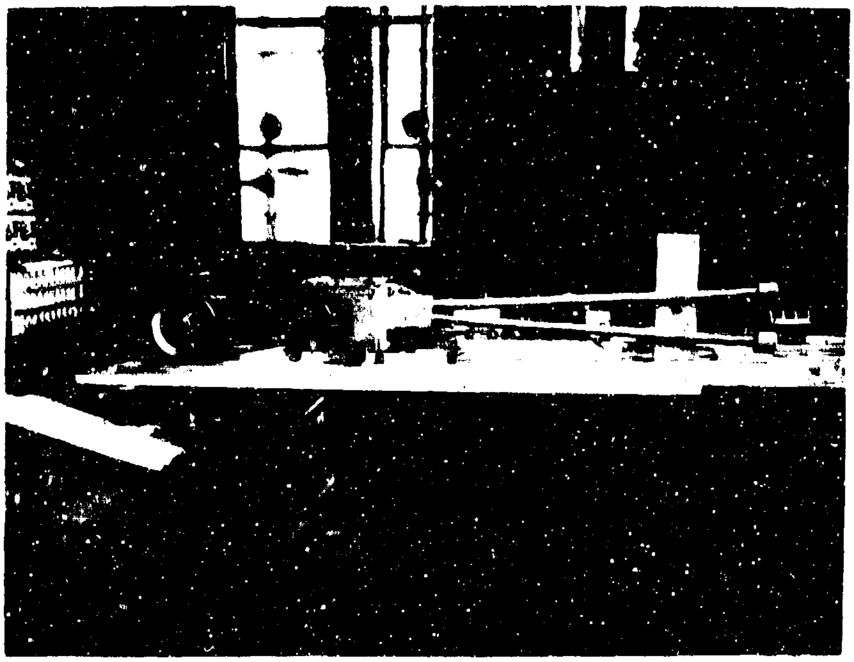


Figure 1 -- Collector Ring Function



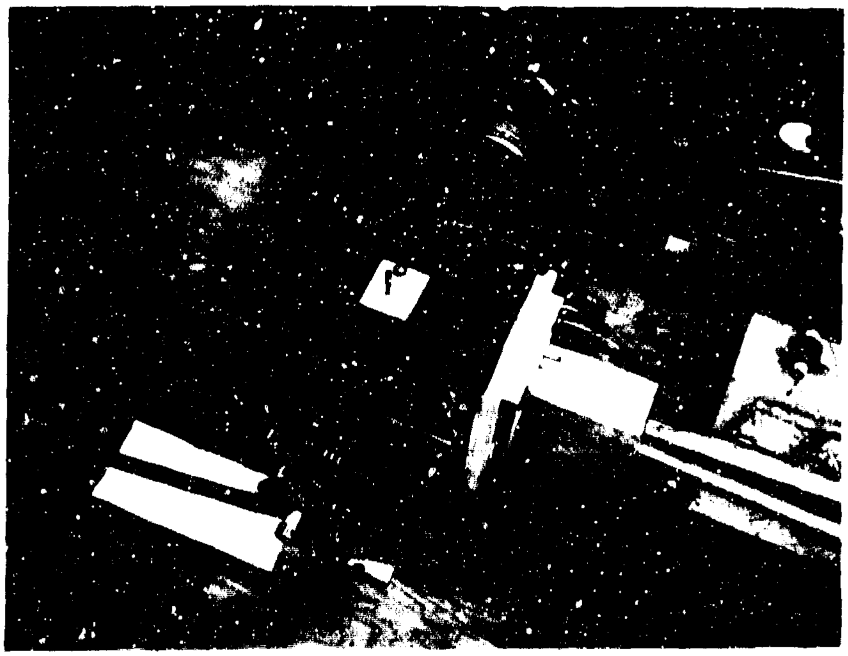


Figure 2 -- Breadboard Valve for the Reverse-Blowing Circulation Control Rotor Model

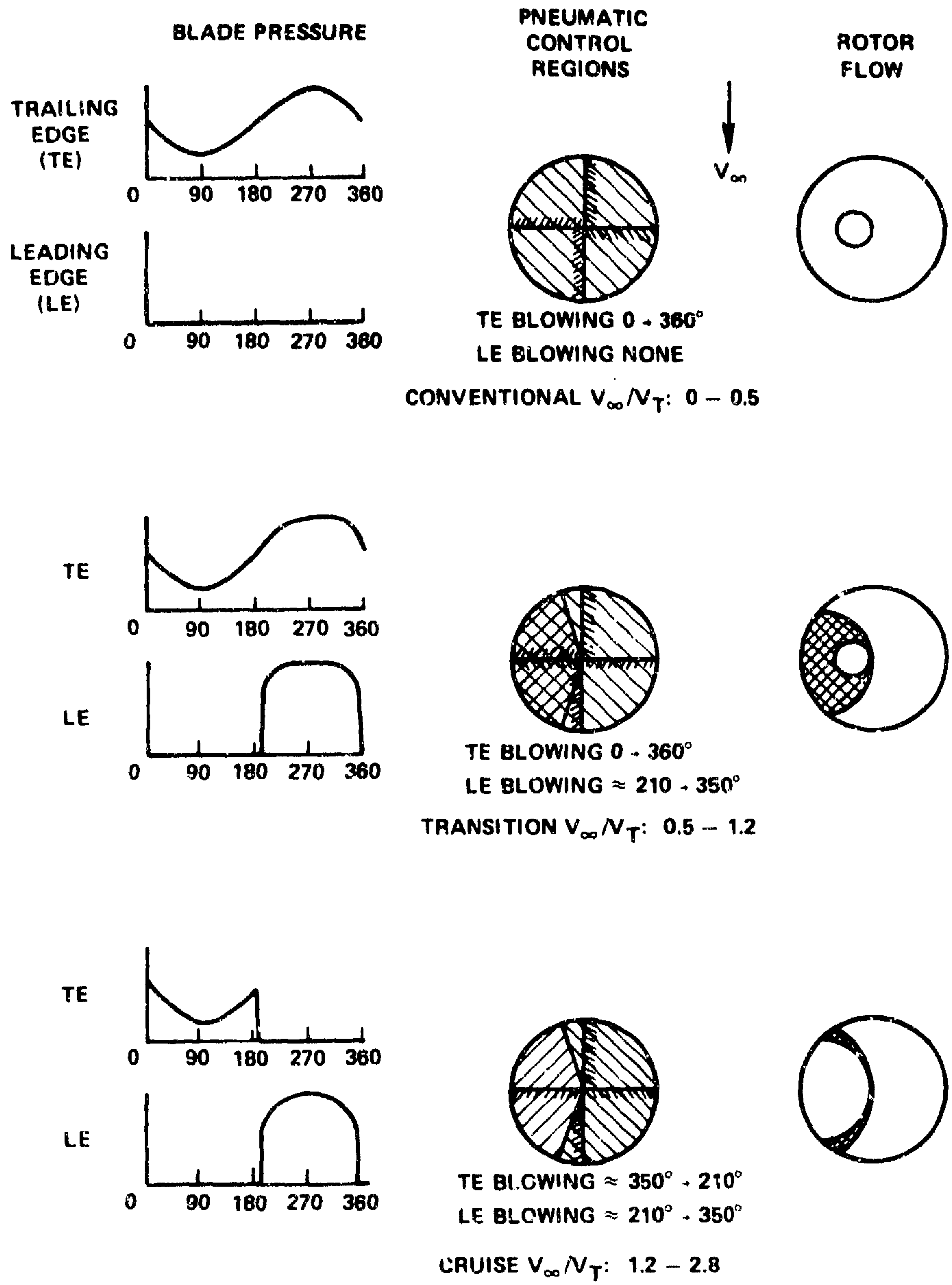


Figure 3 -- Control Requirements for the Reverse-Blowing Circulation Control Rotor

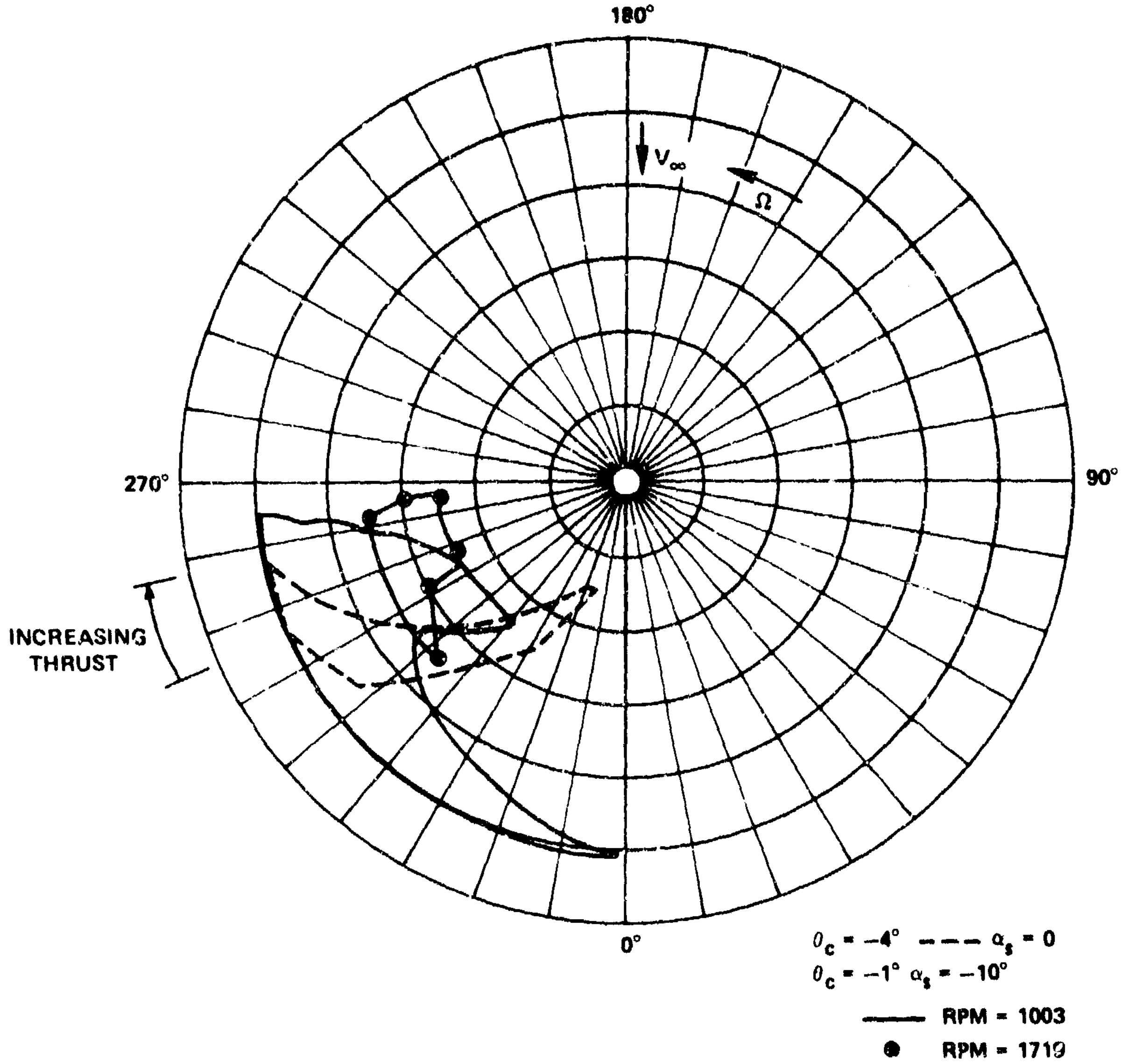


Figure 4 -- Control Input for Maximum Pressure for the Circulation Control Rotor Model (CCR2)

Figure 5 -- Pressure Wave Required versus Cam Azimuth Position

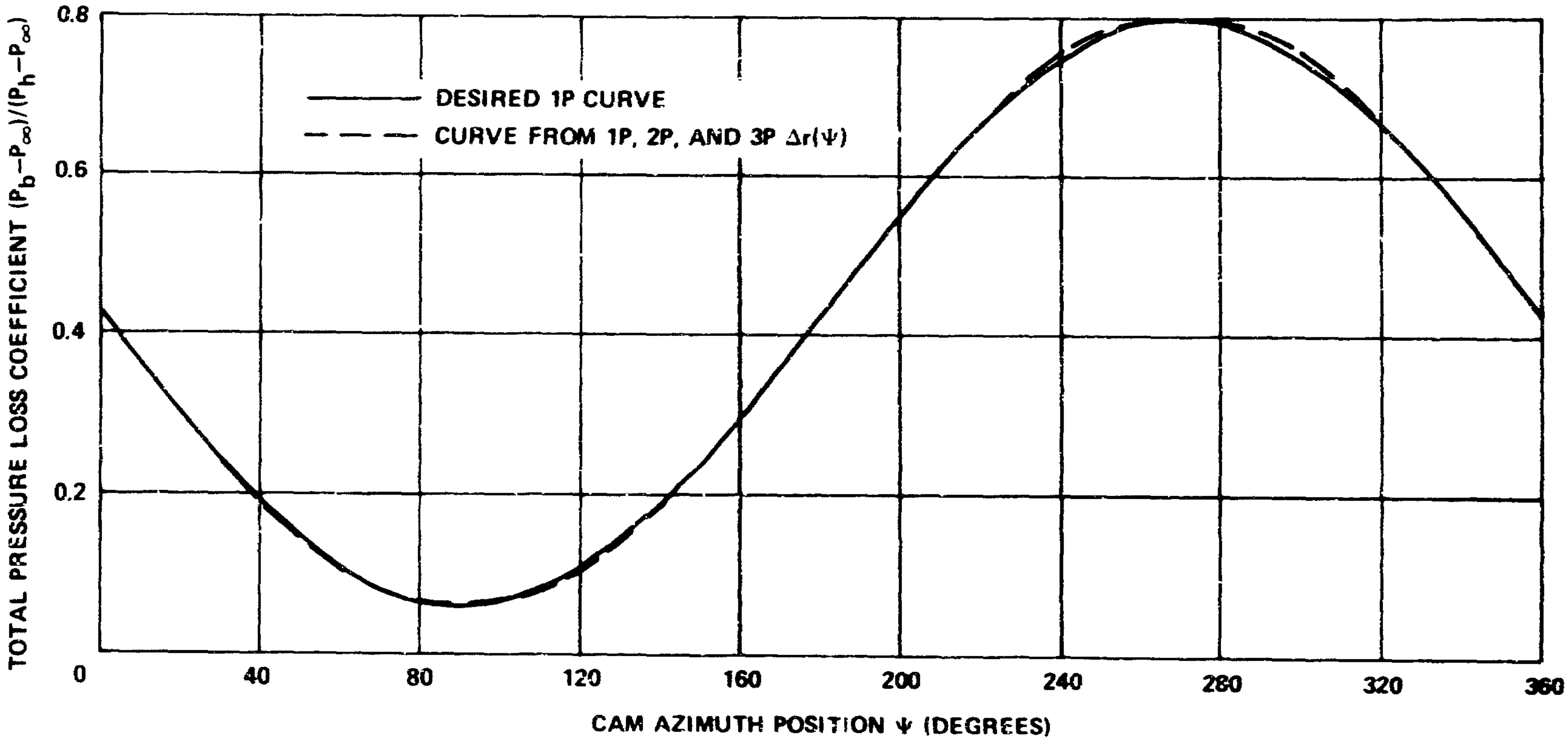


Figure 5a -- Pure One-Per-Rev Input, 2P = 0

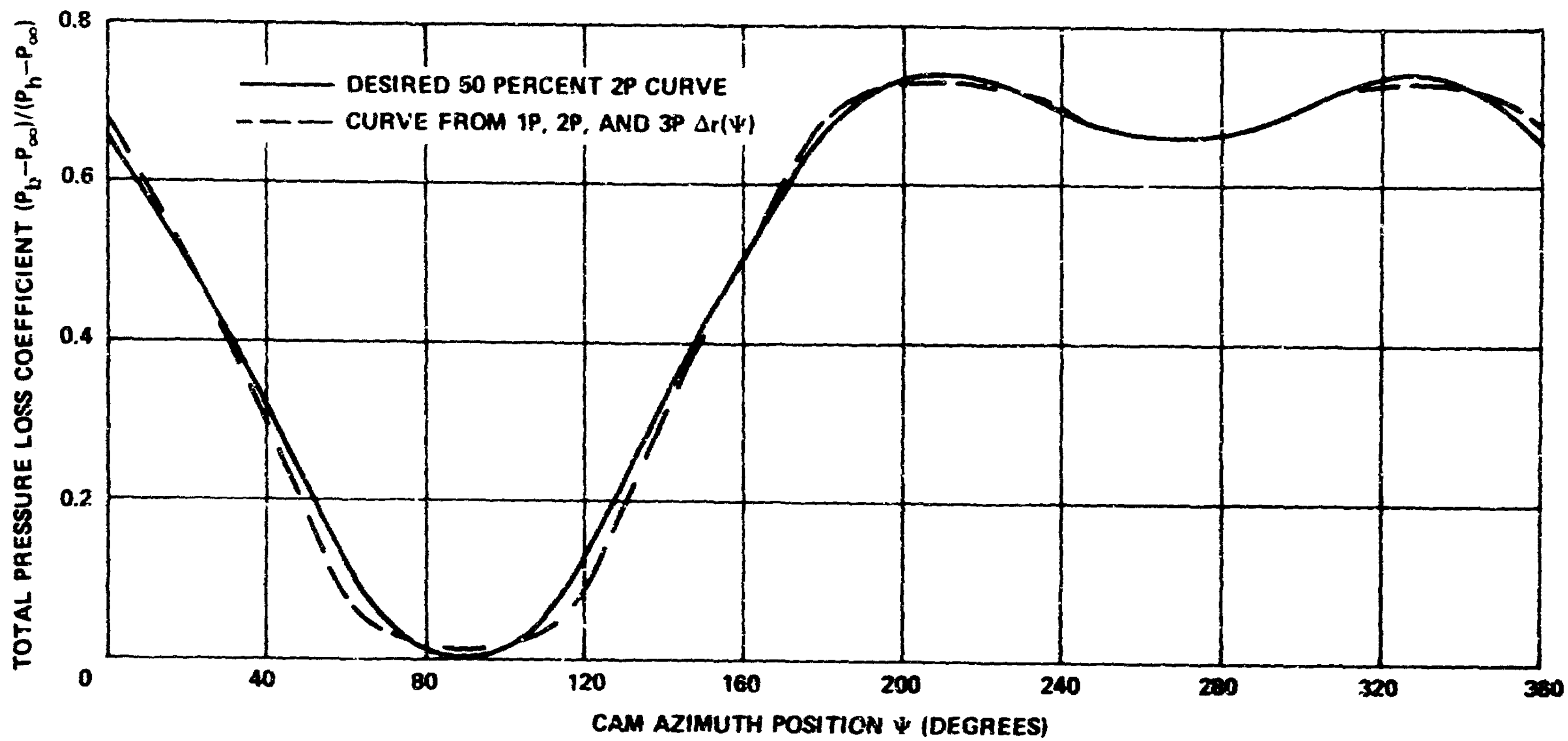


Figure 5b -- One-Per-Rev Plus Two-Per-Rev Input, 2P = 0.5 1P

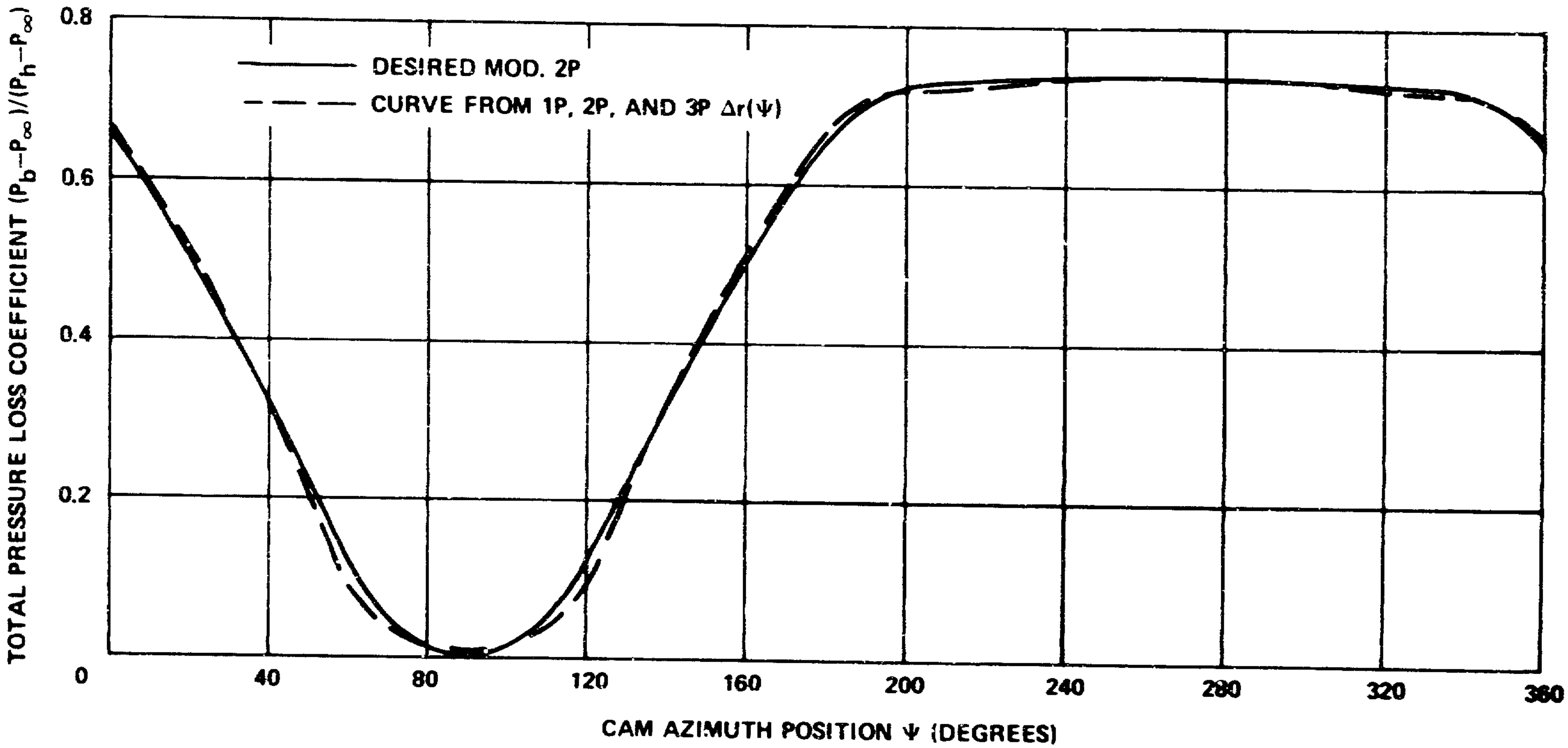


Figure 5c -- One-Per-Rev Plus Two-Per-Rev Input, 2P MOD

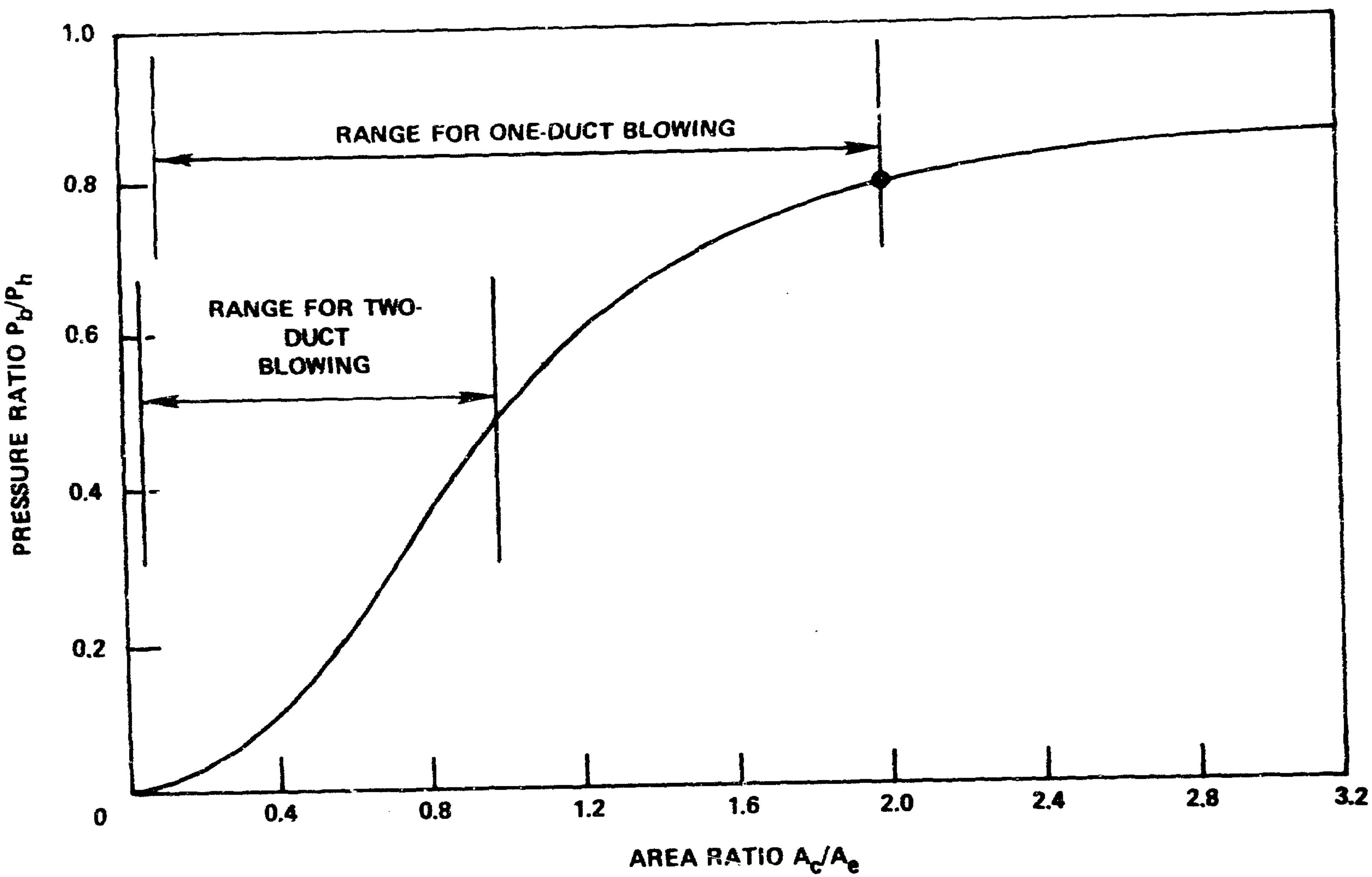


Figure 6 -- Effect of Two-Area Design on Pressure Recovery

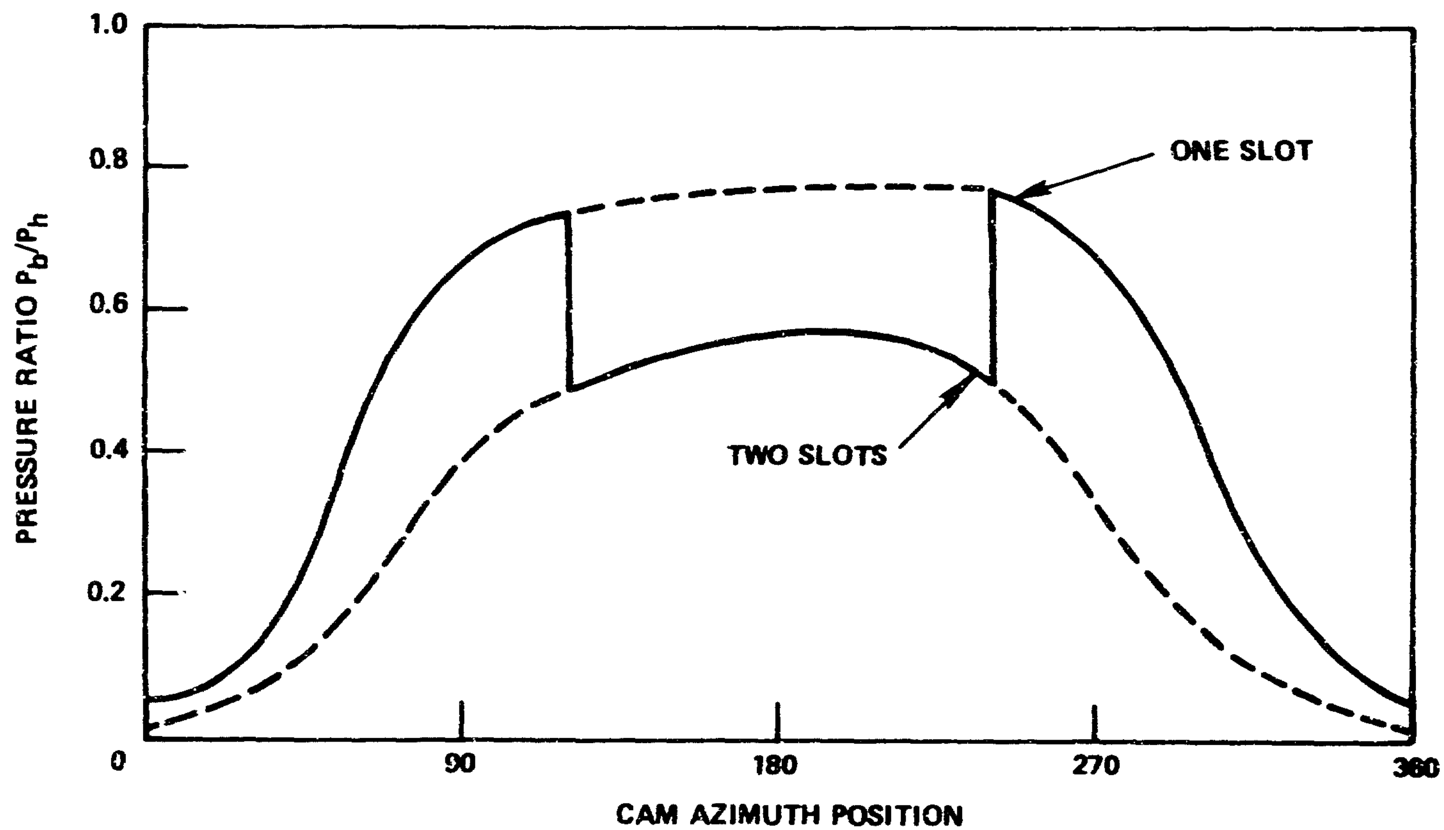


Figure 7 -- Effect of Area Change on the Pressure Recovery Due to One and Two Slots

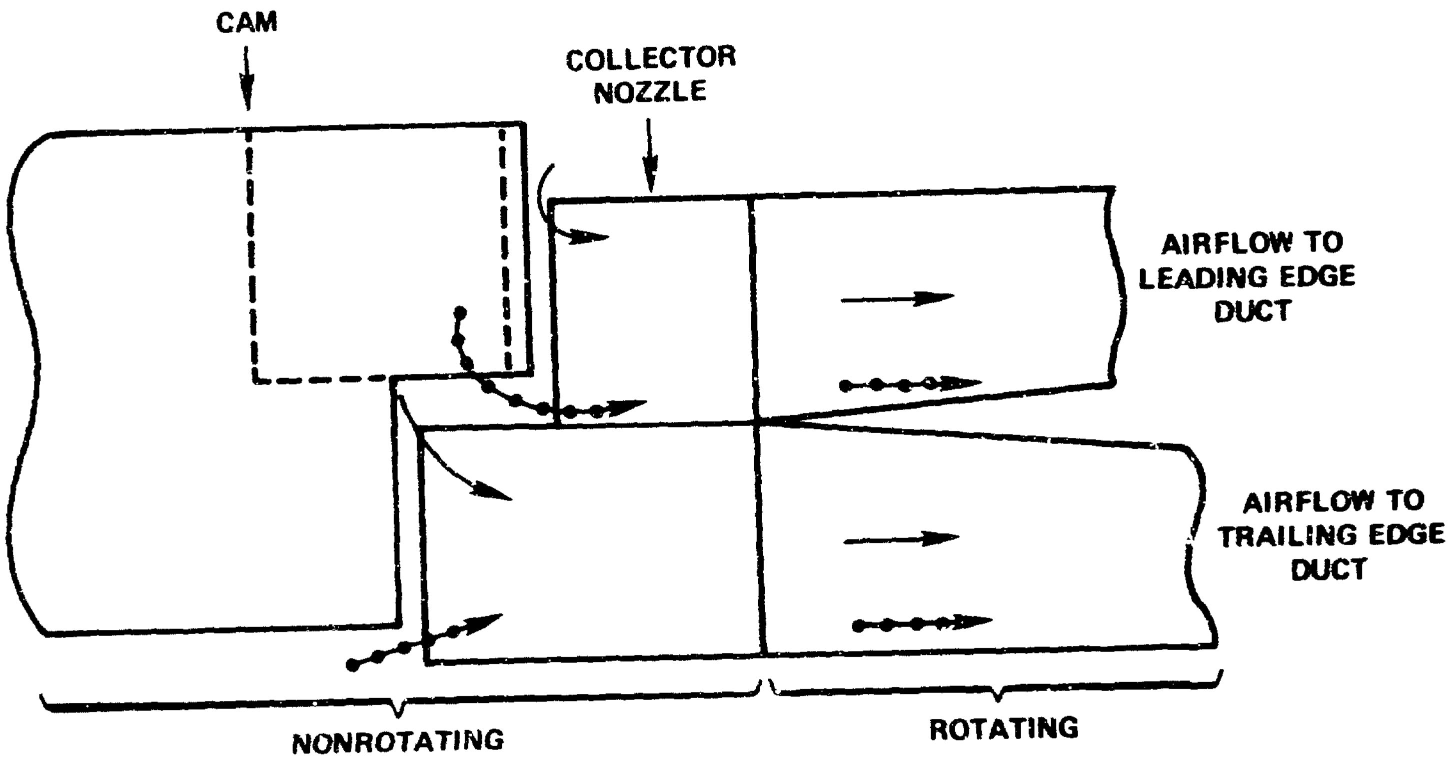


Figure 8 -- Collector Nozzle Function

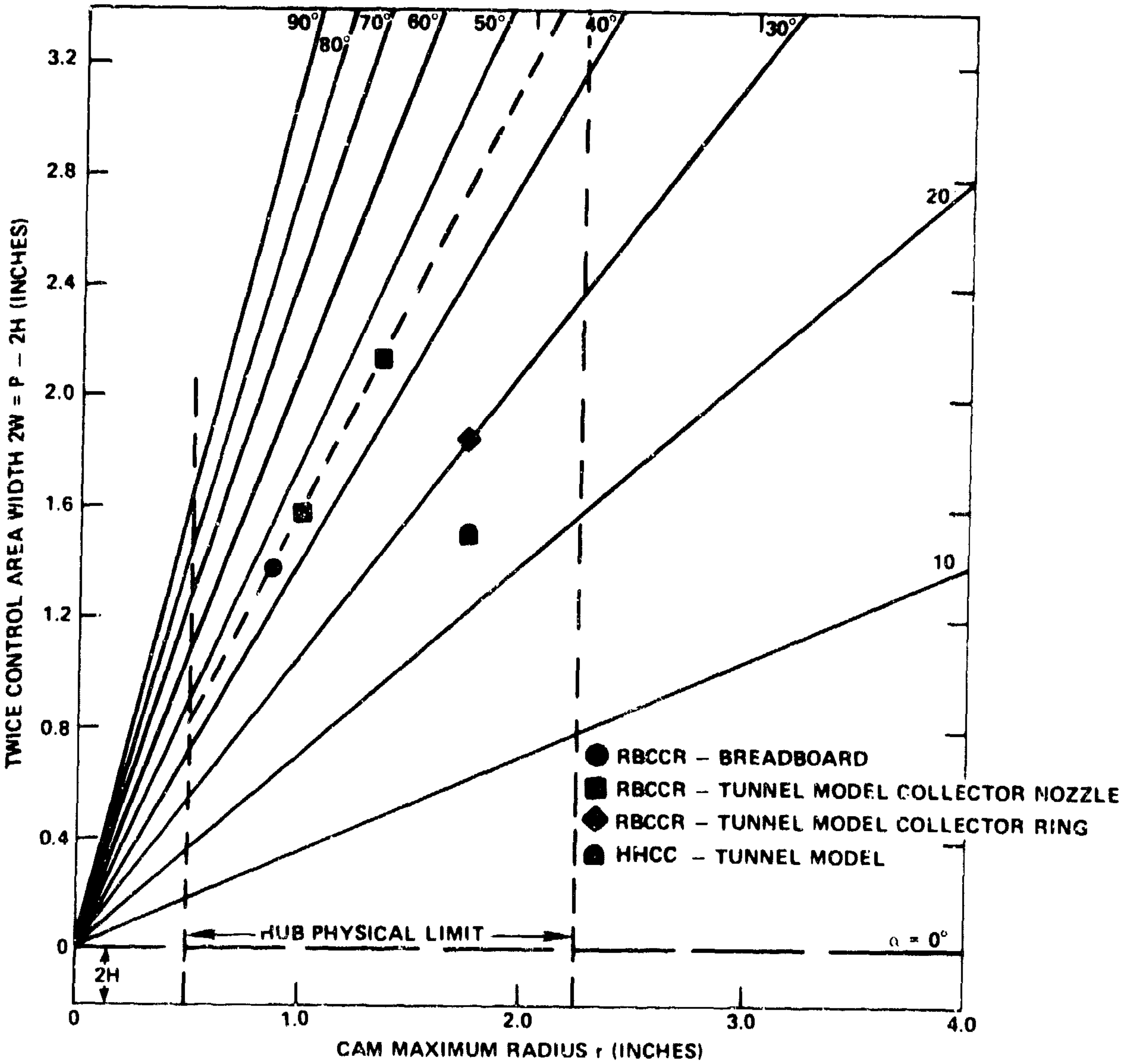


Figure 9 -- Sensitivity of Parameters Which Define the Peripheral Length of the Nozzle

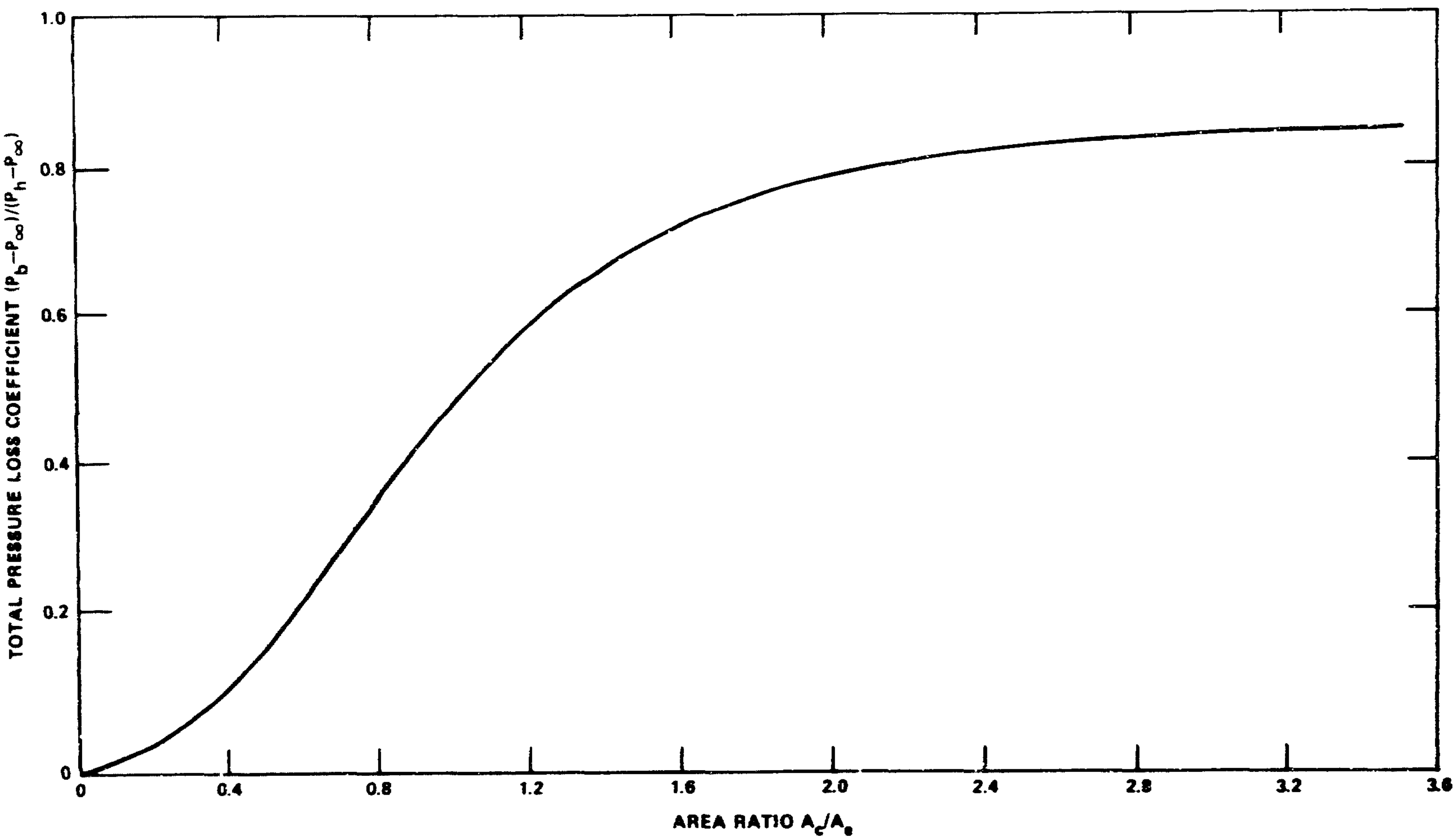


Figure 10 -- Reference Curve of Pressure Ratio versus Area Ratio for Valve Design

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